Integrating Mussel and Kelp Longline Culture Structures and Management – PI Lindell

I.1 Introduction/background/justification:

Mussel (*Mytilus edulis*) farming and sugar kelp (*Saccharina latissima)* farming have been two of the fastest-growing sectors of marine farming in the Northeastern U.S. over the past ten years. The number of mussel farms has climbed from two or three raft-based farms in Maine to more than a dozen, including three offshore farms in NH, MA and RI. There were no seaweed or kelp farms a decade ago, and now there are at least a dozen spread between ME, MA, RI and CT. Markets are robust for both crops and the only substitutes are from a dwindling and erratic wild supply or imports of inferior quality and freshness. Given that both these crops are individually being grown on the same basic longline structures on private leases in public waters, it makes sense to integrate the cultivation of the crops for several reasons; (1) better space utilization of limited permitted sites – "3D farming", (2) shared use of the capital costs of expensive anchors, lines, buoys, (3) better risk management via crop diversification, (4) lower risk to protected species by using fewer vertical lines per unit of production. The additional benefits of using multiple complementary nutrient bio-extractive crops are improved ecosystem services such as (i) improved water quality, (ii) provision of structure resulting in nursery and foraging habitat for other species, and (iii) a sustainable seafood supply (Rose et al. 2016).

This research will advance marine aquaculture over the two-year project term by developing (i) innovative gear designs that integrate two different crops into an offshore lease area, (ii) new engineering and *in-situ* trials to make offshore longline aquaculture more efficient and safer for protected species, (iii) methodology for efficient management and harvest of a dual-crop culture system, (iv) a working group (a community of stakeholders), with outreach materials and a workshop dedicated to resolving technical and regulatory issues.

This information is a critically needed by State and Federal agencies (many of whom will be represented on our working group) that are currently reviewing or engaged in providing information relevant to new permit applications for new species like seaweed (see letters of support).

I.2 Kelp and Mussel Aquaculture in the US and around the World

Kelp: On a global basis, seaweed aquaculture is roughly a US $6 billion industry and represents 30% of world marine aquaculture production by weight (FAO 2016). At present, the annual global output of kelps (various species) is about 10 million metric tons with over $1.4 billion annual value (FAO 2016). Kelps have historically been used as human food (e.g. sea vegetables) and there is renewed interest in young, tender, cultivated kelp among health food advocates and gourmet chefs alike. Kelps have also been used as a major source of iodine for nutritional supplement and alginate as food additives, and they have been viewed as a potential biomass for biofuels. Finally, kelp aquaculture has attracted interest from the environmental policy and marine scientific research communities as a potential means of nutrient bioextraction to restore eutrophic waters, to absorb CO_2, and as complementary way to improve water quality around fish and shellfish farms (via IMTA – integrated multi-trophic aquaculture)

The adoption of sugar kelp farming in the US is very recent and was initiated through a partnership between UCONN (and co-PI Yarish) and a private company, Ocean Approved via an NOAA-funded SBIR program initiated in 2010. This successful Phase I and II program grew sugar kelp following UCONN's nursery technologies for the seedstock, and marketed their freshly frozen products to food service companies, health food stores, and supermarkets in the US. An outreach component to the research included the publication of a how-to manual, as well as instructive public workshops. Since then over a dozen farms have started farming sugar kelp in New England many of whom are still associated with UCONN.

Among the early adopters of the sugar kelp growing technology in Southern New England in 2012 was Bren Smith of Thimble Island Aquaculture Farm in Branford CT. After 5 - 6 months (December-May) in LIS, kelp sporelines (1 to 2 mm) grew to 3 m in length, with a yield of over 18 kg fresh weight per meter of line (Kim et al 2015). The estimated biomass yields of sugar kelp could be up to 29.2 – 116.7 MT FW ha^{-1} or more depending on the spacing of the longlines (1.5m-6m). Mr. Smith has since also formed a non-profit research and educational institute, GreenWave, whose mission is to create a network of shellfish and seaweed farms extending along the New England coast. Mr. Smith's experience with kelp culture in the field, and with processing (developed by co-PI Yarish) and marketing will be instrumental to gathering quality field and marketing data as well as public outreach and demonstration opportunities.

Mussels: There are many successful examples of sub-tidal and offshore shellfish farming around the world. By far the most successfully cultured are various species of mussels. Over 1.8 million metric tons (4 billion lbs.) of mussels were harvested worldwide in 2011 with the United States contributing only 0.7% according to the FAO. Of the $108 million worth of live mussels consumed in the United States in 2011, more than 85% were imported from Canada. Another $70 million of processed mussels were imported to the US from New Zealand in 2011 (aquaculturenz.org).

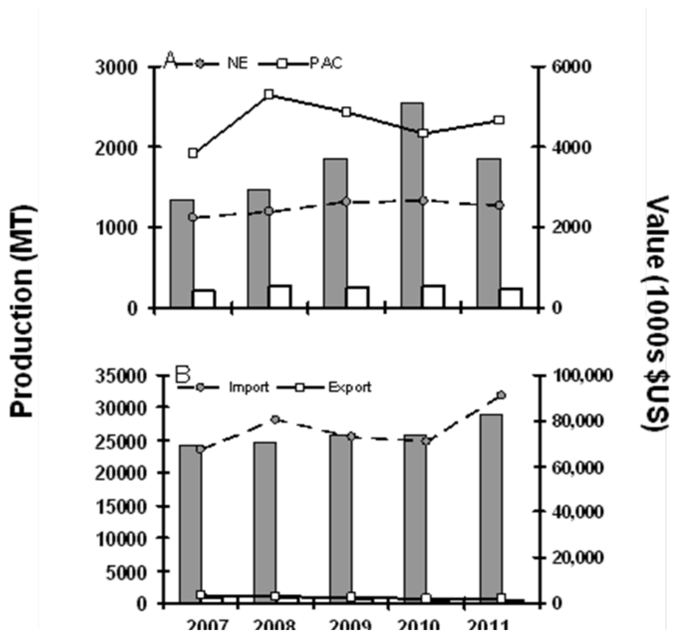

Figure 1. A) Comparison of total production in metric tons and value for blue mussels harvested in the Northeast (NE; grey bars and dashed line, respectively) and the Pacific Northwest (PAC; white bars and solid line) of the U.S. over 5 years. B) Comparison of blue mussel imports into and exports from the U.S. over five years. Panel A is from NOAA annual landings reports at http://www.st.nmfs.noaa.gov/st1/commercial/landings/annual_landings.html while data for panel B drawn from USDA report on aquaculture imports and exports, http://www.ers.usda.gov/data-products/aquaculture-data.aspx

Mussel culture is a highly productive sector of the shellfish culture industry in the northeastern U.S. The production of blue mussels in the region has increased steadily in surpassing 2500 metric tons 2010 (Figure 1A). Local, regional and even international markets are receptive to New England mussels. Given a history of market acceptance and steady growth, the industry is poised for further expansion through both increased production on individual farms and through entry of new farms into the industry. In the last few years new mussel farms have started in Connecticut (CT; Thimble Island Ocean Farm, Bren Smith co-PI), Rhode Island (RI; new leases to Salt Water Farms and American Mussel Harvesters)

Massachusetts (MA; Menemsha Fish Market, Stanley Larsen farmer for this project), New Hampshire (NH: Flanagan and Prien) and Maine (ME; Cooke Aquaculture, Trundy Point and Wild Oceans Aquaculture). Such expansion will allow New England growers to command more of the market and help to reduce the tremendous trade imbalance for seafood that currently characterizes the U.S. market where mussel imports from Canada, Chile and New Zealand vastly outweigh domestic production (Figure 1B).

Over the last ten years, four independent enterprises in California, New Hampshire, Rhode Island, and Massachusetts were granted permits and have been farming mussels using longline technology in truly exposed sites where many predict the future of mussel farming can thrive with fewer potential user conflicts. Three currently permitted sub-tidal farmers are collaborating on this proposed project, including an exciting new network of aquafarmers that have joined the GreenWave movement to develop "3-D farming" starting along the Connecticut coast.

I.3 Opportunities and Benefits of Kelp/Mussel Co-culture

The advantages of growing multiple crops rather than just one has been a part of agricultural risk management for millennia. Crop diversification may lower the risk of crop failure and fluctuations in pricing. Farmers growing both crops would enjoy an expanded seasonal market which tends to be just April, May and part of June for fresh kelp while mussels can be sold fresh throughout the year. Fresh kelp can be processed and frozen for sale at other times of year.

Besides economic risk management, the economic opportunities from culture of these crops helps to advance the stability of coastal communities in the face of dwindling wild fisheries. Shellfish and seaweed aquaculture rank high among the most sustainable sources of seafood while also providing valuable jobs, and working waterfronts. Kelp's primary growing season in the winter-spring corresponds to a period when shellfish farmers have spare time and need income, and therefore provides important employment opportunities.

Integrated co-culture of mussel and seaweed could be more productive than monocultures. Mussels are prolific filter feeders that can clear the water and improve light penetration for kelp photosynthesis and growth. Mussels metabolically excrete ammonia into the surrounding water that kelp may usefully consume for growth. We expect kelp to grow better on an integrated farm, particularly in areas or seasons when light or nitrogen is limiting (e.g. late spring). Kelp beds and mussel farms have demonstrated utility as valuable habitat for forage species, and for young stages of fish important to the recreational and commercial fishing industries.

Integrated mussel and seaweed culture offers opportunities to improve ecosystems. Sugar kelp accumulated nitrogen (N) up to 3% of dry weight in studies of its commercial culture in the eutrophic headwaters of Long Island Sound (Kim et al 2015). The potential N removal could exceed 280 kg ha^{-1} yr^{-1} from Long Island Sound (LIS). Kelp is also an important CO_2 sink and the duration of net CO_2 removal can be extended if the biomass is used in environmentally friendly ways (Chung et al. 2013). Kim et al. (2015) estimated that sugar kelp could sequester up to 1,800 kg ha^{-1} of C per year in LIS. Considering the most recent nutrient credit values in the U.S. for these two elements (\$12.37 kg^{-1} N, \$6.00 – \$60.00 mt^{-1} C (as CO_2); CDP 2013, CT DEEP 2014), the potential economic values of C and N removal from seaweed alone could exceed \$3,000 ha^{-1}. This could be additional income for seaweed growers beyond the value of seaweed products, if incorporated in the Connecticut Nitrogen Credit Trading Program and a carbon-pricing scheme (http://www.ct.gov/deep/lib/deep/water/municipal_wastewater/9_17_14_pres_futureplans_ntp.pdf). The quantity of C and N per ha that could be extracted via mussel farming would be at least double that of seaweed (Barrington et al. 2009, Lindahl et al. 2005). Additional potential environmental benefits of longline structures nearshore in places like LIS include dissipation of wave energy and shoreline stabilization (Kim et al. 2013).

The perceived potential risk of marine mammal or sea turtle entanglement associated with relatively new applications for offshore and subtidal shellfish aquaculture in the U.S. is proving to be a severe impediment to the expansion of aquaculture. This is particularly true if it involves typical submerged longlines used for mussel and kelp farming. Regulatory issues pose a barrier to business growth at the same time that market demand for local mussels and kelp is poised for expansion.

This project will directly address this constraint by identifying and documenting the efficacy of gear modifications aimed at reducing the number of vertical lines that are thought to pose an entanglement risk. We will do this by combining mussel and kelp culture on the same vertical lines (and anchors) thus reducing the number of lines by half. We will also examine ways that an array, using just eight well-spaced anchor and vertical lines, can support a much larger array of horizontal lines supporting kelp and/or mussels, as well as spatial and seasonal management measures that could be adopted. Our results will inform industry and regulatory staff on how to prudently allow the shellfish and seaweed aquaculture sectors to expand without putting protected species in peril. While our focus will be on specific engineering and management issues and risk mitigation measures confronting aquaculture in New England, our approach will have far broader application and will serve as a model for confronting similar problems in other states and regions such as the Southern California Bight where these business activities are being separately proposed but could be jointly pursued some day. California Sea Grant is funding a permitting process for mussel farming, and DOE/ARPA-E is funding kelp-farming research in the same region.

I.4 Challenges and Potential Drawbacks or Risks of Co-culture

The main challenges associated with co-culture are engineering and technical management. The typical timing of planting mussel seed (September through December) and kelp seeding (October – November) provide overlapping choices in the autumn. If the two crops are to be integrated on one horizontal headrope of a longline, it makes sense to plant the sugar kelp seedstring first and then wait for for it to get established before hanging mussel socks on the same line. This set-up will damage a 3 to 5 cm section of kelp every 1 m where mussel socks and buoys are tied (an estimated 5% kelp loss). More kelp may be lost or damaged each time the longline is hauled for inspection and to add buoyancy. A properly tensioned longline might need such maintenance once a month in the wintertime leading to another estimated 10% loss of kelp. When it comes to harvesting the kelp in the spring, the inter-cropping with mussels will slow the efficiency with which that takes place. If the headrope is suspended at the typical optimum depth for kelp at 2m from the surface, then there could be a risk of storm damage to mussels that are typically suspended well below damaging wave action.

If an additional lighter headrope line dedicated to kelp is added above the main headrope from which mussels are hung then a different set of advantages and disadvantages prevails. In this configuration it makes sense to plant the mussels first at depths below likely storm damage (3 to 8 m). Then the kelp seedstring can be planted at an optimum depth above the mussels with minimum disruption. The challenge then becomes accessing the mussels for the required monthly winter maintenance without damaging the kelp above. We share some ideas to address this challenge in the research plan below. This becomes a non-issue for mussel culture once the kelp is harvested in the spring.

I.5 Integration of this Proposal with Current and Pending Projects

This project complements PI Lindell's currently funded Saltonstall-Kennedy (S-K) project NA14NMF4270034 "Expanding Opportunities for Blue and "Gold" Mussel Farming in New England from Hatchery to Grow-out", and builds on a nearly 10 year history of cooperative academic/industry research for improving longline mussel culture. This research has developed low-cost means of producing mussel seed when wild mussel sets prove sparse or erratic.

This project complements PI Lindell's currently funded Saltonstall-Kennedy (S-K) project NA14NMF4270035, "Developing Whale and Turtle-Friendly Sub-tidal Aquaculture Gear" and another one funded by the National By-catch Reduction Engineering Program (BREP). The S-K project, due to end summer 2017 (including an expected 1 year NCE), has demonstrated advancements in anchoring technology for offshore aquaculture, and the utility of modifying or stiffening the vertical lines directly under buoys as will be conducted in our proposed experimental double longline configuration for this project.

This proposed project will follow a currently funded USDA-NIFA project "Developing An Environmentally And Economically Sustainable Sugar Kelp Aquaculture Industry In Southern New England: From Seed To Market lead by co-PI Yarish and co-PI Lindell to make advances in the development of commercial seaweed nurseries and in the post-harvest processing of sugar kelp. The project is due to conclude August 2016.

This project also complements co-PI Goudey's recently approved NOAA SBIR project "Engineering Structures for Offshore Macroalgae Farming" that will identify and prove the feasibility of innovative, commercial-scale systems and methods for the cultivation of macroalgae on the high seas. Part of that project will generate drag data on cultured kelp, essential to the engineering of reliable systems for kelp culture.

This project complements co-PI Smith's pending NFWF Project, "Ocean Farm Start-Up Training Program and Processing Center Expansion in New England" that will create eight new economically viable 20-acre ocean farms in Southern New England and expand a seaweed and shellfish processing center in Fair Haven, CT.

II. Research Work Plans

II.1. Overview – There are six research hypotheses we aim to test with this proposal:

1. We can plant kelp and mussels on single and double head ropes suspended between a single pair of anchors and anchor lines with associated buoys.
2. We can manage the mussels (i.e. check the lines and periodically add buoyancy) without significantly damaging the kelp or mussels.
3. We can design the longline system for shallow waters (7 to 9 m) such that mussels are adequately protected from storm damage, and are still commercially productive by manipulating the density and spacing of the mussels.

4. The growth rates, yield and quality of mussels and kelp grown on an integrated longline is the same or better than those grown on separate control monoculture lines.
5. We can establish a multiple headrope catenary array (Figure 2) with fewer anchors and vertical lines than typically required for kelp and/or mussel culture on single longlines, and at significantly less cost.
6. Our economic modeling shows significant economic and ecological benefits of integrated co-culture of kelp and mussels compared to single crop cultivation.

Research Objectives and Tasks: The objective of this research is to develop and demonstrate ways of integrating mussel and kelp farming into a single longline structure. During the second year, in parallel, we will develop and deploy a catenary array design for a more compact and a lower cost structure for kelp culture shown in Figure 1, and to test whether it might be suitable for mussels as well.

Objective 1 - Plant kelp and mussels on a single longline.

Objective 2 - Demonstrate that mussel and kelp cultures can be managed together

Objective 3 - Determine optimum culture densities of mussels at given sites

Objective 4 - Compare the growth rates, yield and quality of co-cultured mussels and kelp

Objective 5 - Establish and test a multiple headrope catenary array

Objective 6 - Develop an economic model of to compare co-culture with monoculture crops

II.2 Research Plan Details

Task 1 (Yr 1) - Dual-purpose integrated longline development.

Both mussels and kelp can be grown on longlines but heretofore they have never been purposely cultured together on the same longline, to our knowledge. The advantages seem obvious with respect to reducing by half the amount of gear and operational footprint compared to culturing them independently. However, the standard methods of culture vary sufficiently that macroalgae growth on mussel longlines is typically discouraged and monocultures are favored.

1a. Single headrope design - Through the proper selection of substrate, deployment details, and timing, we will install single 100 m longlines with dual-purpose headropes. In this trial configuration, kelp seedstring will be unspooled in a spiral fashion around along the length of, and be integral with the structural headrope that is tensioned and suspended between large submerged corner buoys and opposing anchors (Figure 1). After the kelp is planted, mussel socks with 1 meter spacing between them will be tied to the same headrope. Variations in tide level (1 to 2 m at our sites in LIS) are absorbed by the weight of the anchor chain. Even at low tide the linear system will be taut which is important to avoid entanglement risks to marine mammals and turtles.

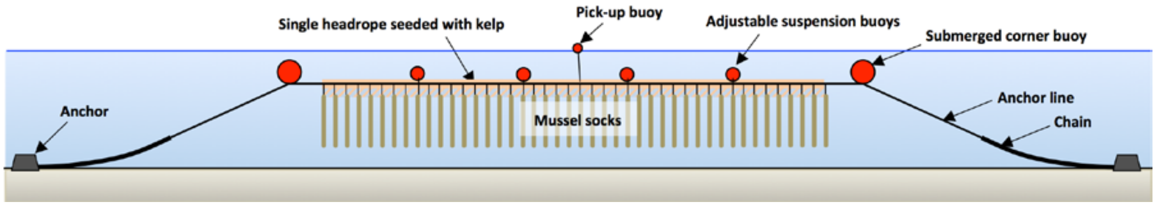

Figure 1. The dual-use single headrope system design.

In Year 1, such single co-culture headropes will be located approximately 2 m below the surface, a depth determined as suitable for kelp growth in LIS based on previous UCONN and GreenWave studies (Kim et al. 2015). The number and placement of submerged buoys (surface buoys will only mark the ends of the line and the center to facilitate lifting the line) will depend on the biomass that needs to be supported and will be adjusted according to growth and harvest cycles. At a second site in Vineyard Sound with greater wave exposure, we will install a single co-culture longline at 3 m depth.

1b. Double headrope design - A second trial configuration involves the addition of a second parallel headrope (longline) for kelp independently seeded and suspended above the mussel headrope (longline) as shown in Figure 2 below.

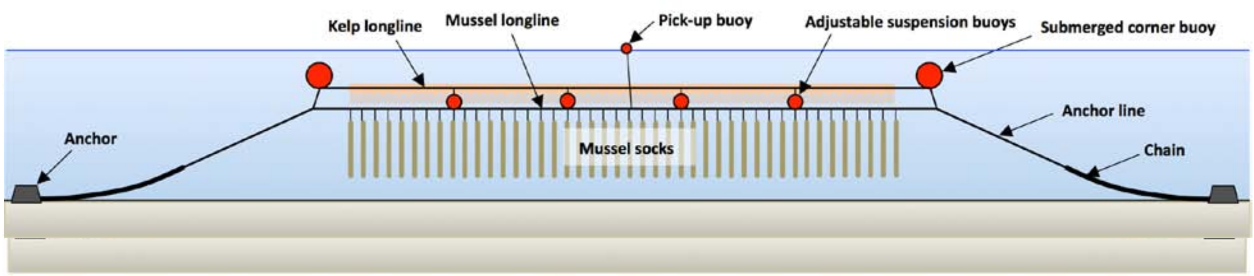

Figure 2. The double-headrope longline design.

This kelp line is separated from the mussel line by means of connecting sheathed vertical lines at each corner that allow the kelp line to deflect out of the way when the mussel line is hauled to the surface for tending. In Year 1 at LIS farms, the mussel headropes will be suspended at 3m depth while the paired kelp headropes will be supported above them at 2 m. Given the greater depth available in Vineyard Sound, the double headrope configuration will suspend mussels at 6 m deep with kelp above at 3 m deep. Since we have not cultured kelp at this site, we will also deploy 3 kelp lines (6 m long) vertically from surface buoys to the mussel headrope to determine the optimum depth at which it grows in these exposed and more oligotrophic waters.

Specifically, with four parallel 100 m lines fitting to an acre (separated by 10 m), we will install three single headropes and three double headropes at both LIS sites, and one of each at the Vineyard Sound site for evaluation in Year 1. Replicate monoculture control lines of kelp and mussels will be planted in the same way at the same depth and time in LIS. With its limited number of lines, we will only have replicate control lines of mussels in Vineyard Sound. "HOBO" temperature and light data loggers will be attached to a kelp line to track environmental variables for each farm. The yield of kelp and mussels will be determined at harvest approximately 6 months and 12 months after planting, respectively, and compared to the control lines at each site. See Task 4 for harvest and yield analysis.

Kelp seedstring will be provided by UCONN in Year 1 where their hatchery/nursery has consistently provided supply for 6 years to industry and research cooperators. Year 2 kelp seedstring will be produced by GreenWave with advise from Dr. Yarish and his staff at UCONN. Mussel seed local to each farm will be collected from spat collecting ropes. PI Lindell has a special socking machine and the requisite continuous ropes and cotton for appropriately planting the mussels (600 seed/m on 2 m length socks spaced every m) at each farm that he and his staff will oversee.

These systems will be designed by co-PI Goudey and installed at Thimble Island Ocean Farms (Bren Smith), and at the farm of GreenWave farmer apprentice, Asa Dickerson in LIS, and, and at Menemsha Fish Market's farm in Vineyard Sound (see letters of intent and matching funds pledged). Engineering analysis tools will be used to ensure structural adequacy under all conditions of tidal level and flow conditions. Data obtained by Goudey in a companion SBIR project will be used to model drag forces on the kelp (and mussels) at various stages of growth. Cadre Pro software will be used to model array shapes and component tensions.

Task 2 (Years 1 and 2) - Develop techniques for managing a dual-use integrated longline.

As described in section 1.4 of this proposal, there are challenges associated with managing a dual-use longline with single and double (horizontal) headropes. Some of these can be addressed with scheduled planning each autumn.

2a. Managing a single headrope will require that kelp seedstring be planted first because it is essential to properly establish the kelp plants. Approximately 4 weeks later, mussel socks will be planted every meter along the headrope. Appropriate submerged counter-buoyancy will be added and proper sub-surface tension will be applied to provide a stable platform that can withstand storms. Once a month during the 6-month kelp growing season (November to April) the longline will be lifted via a small center pick-up buoyed line to the surface, and additional buoys will be added to counter-balance the growing crop mass. At harvest time in the spring, the kelp will be cut from the longline in 1 m sections between mussel socks. The mussels will continue to grow to be harvested at market size (50 to 60 mm) in late summer and early fall.

2b. Managing a double headrope requires that mussels be planted first in the autumn on the lower headrope followed by kelp on a lighter parallel hearope above. Separating the two parallel lines will be HDPE sheathed vertical lines that will help keep these two lines separated when the mussel line is pulled to the surface via the center pick-up buoy for monthly maintenance as above. The kelp line will deflect away from the mussel line as it is pulled up, especially if we properly utilize crosscurrents. Additional submerged buoys will be tied close to the mussel line to counter their weight, and will not interfere with the kelp line above. Once again, proper sub-surface tension will be applied to provide a stable platform that can withstand typical storms. At harvest time in the spring, the kelp headrope will be disengaged from the longline and hauled ashore for processing, leaving a typical single mussel longline. As above, the mussels will continue to grow to be harvested at market size in late summer and early fall. Then lines can be cleaned and prepared for another annual planting cycle. See Task 4 for details of harvest and yield estimations.

Task 3 (Year 2) - Determine optimum culture density.

In Year 2, we reserve the option of repeating some or all of our first year experiments in co-culture if our results are inconclusive or the experiments suffer extraordinary storm damage before we can gather enough preliminary data. Based on our conclusions about which configuration works best (single or double headropes), we will investigate the role of mussel density and yield on the economics of co-culture. With shallow-water sites the yield is influenced by how long the mussel socks can hang without the risk of hitting bottom or being too high in the water column where circular wave action can damage them by wrapping the socks around the headrope. But yield is also strongly influenced by the density of planting which is managed, as we intend to do, by the spacing between the socks along the headrope.

The sites in LIS we have selected are prime candidates for our nutrient bio-extractive crops but present some challenges because of limited depth (7 to 9 m). Commercial mussel culture in exposed waters typically requires depths of 20 m or more. At semi-exposed sites like LIS, we estimate that a minimum headrope depth of 2 or 3 m at mean low tide should protect mussels from damaging storm waves. At these shallow depths we need to deploy mussel socks short enough to prevent them from touching and possibly being damaged by or attracting bottom predators. From the information above, we will set our mussel sock lengths to 2 m giving at least 2 m of leeway for managing buoyancy compensation between the seafloor bottom and the mussel socks. Commercial mussel sock lengths typically range from 3 to 10 m but we will make up for the shorter lengths in LIS by testing denser planting along the headrope.

Specifically, in Year 2 we will install replicate co-culture longlines (single or double headropes, depending on first year results) and suspend three mussel headropes with typical 1 m spacing between socks, and three mussel headropes with 0.6 m spacing at the 2 LIS farms. Associated kelp longlines will be at 2m depths. If double headropes are chosen then the mussel headrope will be suspended below at 3m. As in Year 1, replicate mono-crop control lines of kelp and mussels will be planted in the same way at the same depth and time in LIS.

At the Vineyard Sound site, the results of optimum kelp culture depth experiment in Year 1 will determine the depth of our single or double longline configuration in Year 2. Taking advantage of the greater depth at the Vineyard site we will also investigate the role of mussel density by comparing 3 m sock lengths with 5 m sock lengths each spaced at 1 m apart along the headrope. In exposed sites it is not advisable to decrease the spacing. Increasing sock lengths increases the weight on the headrope and lengths over 5 m may compromise the hauling capabilities on the tending boat. Replicate control lines of mussels will be planted in the same way at the same depth and time. Table 1 summarizes the suite of Year 1 and Year 2 experimental and control trials we will conduct.

Table 1. Headrope (HR) Experiments with Mussels and Kelp

	LIS Farms				MV Farm			
	Mussels		Kelp		Mussels		Kelp	
Task	**Experiment**	**Control**	**Experiment**	**Control**	**Experiment**	**Control**	**Experiment**	**Control**
Task 1a Year 1	3 single HRs w/ kelp	3 mussel only HRs	3 single HRs with mussels	3 kelp only HRs	1 single HRs w/ kelp	3 mussel only HRs	1 single HR with mussels	none
Task 1b Year 1	3 double HRs w/ kelp	3 mussel only HRs	3 double HRs with mussels	3 kelp only HRs	1 double HRs w/ kelp	3 mussel only HRs	1 double HR with mussels	none
							vertical lines 0 m to 6 m deep	3 m deep
Task 3 Year 2	0.6m sock spacing	1 m sock spacing	3 replicate single or double HRs w/ mussels	3 kelp only HRs	5m sock length	3m sock length	replicate single or double HR w/ mussels, depth based on 1st year	

Task 4 - To compare the growth rates, yield and quality of co-cultured mussels and kelp

In Year 1 and Year 2, we will conduct regular monthly sampling of the kelp and mussel lines. Specifically we will measure kelp growth by using the hole punch method (Egan and Yarish, 1990) on 30 blades per treatment per farm. Briefly, A small hole will be punched on the blade 10 cm from the junction of the stipe with a cork borer. This is the meristematic region of the kelp. As the new tissue is being produced in this region, the hole will travel distally on the blade to facilitate measurement. Samples of 100 randomly selected mussels will be collected for size frequency measurement. Each month the longline will be examined for damage, predation, and fouling.

GreenWave has a processing facility with appropriate machinery (including the UCONN mobile kelp cutter from co-PI Yarish USDA-NIFA project), and an active marketing and distribution program. GreenWave, Asa Dickerson, and Menemsha Fish Market farms and will carefully weigh the bulk harvestable product of kelp and mussels from each line and also determine the marketable yield in terms of kg per m of headrope.

PI Lindell has a declumper/grader that will be loaned to each farm when they are ready to harvest mussels. Bulk weights of marketable product will be measured post-grading and calculated per meter of sock and linear length of headrope in the case of density experiments. We will also measure the amount of seed that can be re-socked post-grading, a valuable by-product for the next planting season that can amount to up to half of the requirement for re-socking a line. We will measure steamed meat yield of the mussels (meat mass to raw product/shell mass), an important determinant of market quality.

Samples of dried kelp and mussel meats at harvest will be analyzed for carbon (C) and nitrogen (N) content analysis. The tissue N and C will be used to estimate the elements removed per square meter based on measured biomass. The percentages of in the tissue will be determined using a CHN analyzer (Series II, CHNS/O 2400 Analyzer, Perkin Elmer Analytical Division of E.G. & G, Wellesley, MA, USA). Monthly water analyses will be collected for total nitrogen analysis and correlated to N content in kelp. The determination of the carbon and nitrogen sequestration by the kelp and mussels will be used to assign a value to this process. Environmental data from the HOBOs at each farm will be useful to compare to yield data ANOVA, or its non-parametric analog, will be used to assess differences in means between treatments, and G-tests of independence used to analyze differences in size-frequency.

Task 5 – Multiple-headrope catenary array for kelp

The conventional approach for longline culture is similar to that pictured in Figure 1; a single line suspended between opposing arrangements of buoys and anchors. In order to effectively utilize this approach in a normally shaped lease area, the conventional approach is to install multiple longlines parallel to each other and spaced based on the needs for servicing. This results in two sets of mooring lines and anchors per line and requires their precise location and tensioning in order to prevent conflicts between neighboring lines. This explains why the spatially inefficient practice of single or widely spaced longlines predominates.

An alternative approach was developed by co-PI Goudey in a collaborative project with UCONN (Goudey, 2015). Called the catenary array, it is pictured in Figure 3 and allows the efficient use of lease area by providing a stable support structure for multiple longlines optimally spaced for growth and servicing. This project will be the first opportunity to deploy and test this design, a process that is planned for Year 2.

The catenary array greatly reduces the number of mooring lines and anchors while providing a geometrically stable geometry that will reduce interference between neighboring lines. The length and number of lines will be determined based on our first-year findings and project resources.

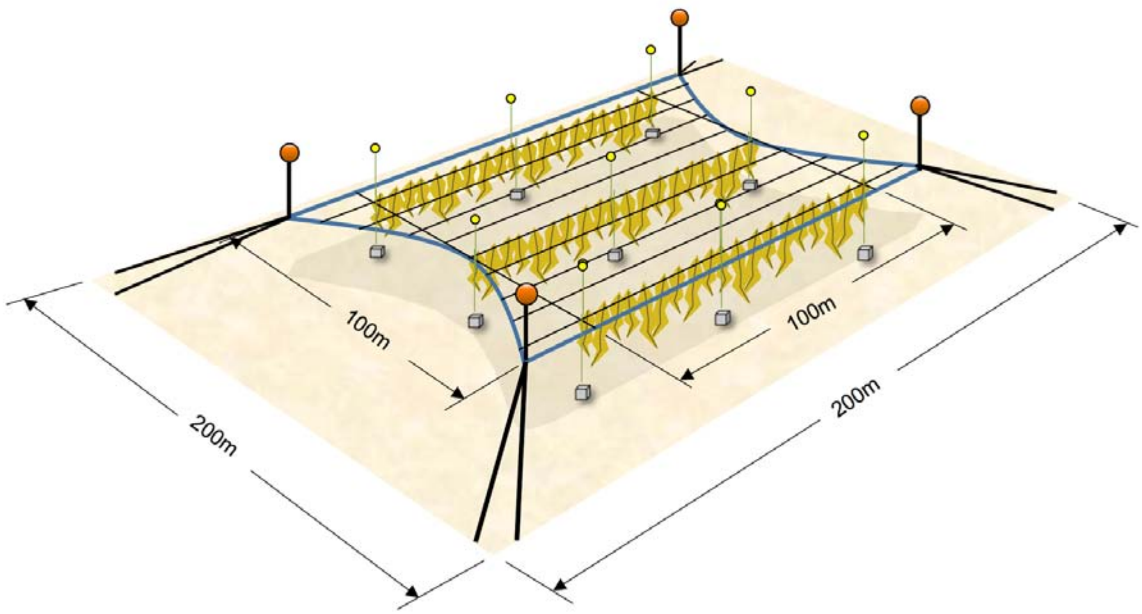

Figure 3. A novel catenary-based longline support structure for kelp farming. (Goudey, 2015).

Task 6 - Develop an economic model of co-culture to compare with mono-culture of crops

We will develop an economic model of commercial-scale integrated kelp and mussel aquaculture operations in southern New England. The model will incorporate cash flow projections, market demand parameters, and production-cost information generated by other components of this proposal. The model will provide insight into efficient scales of commercial joint kelp and mussel farming operations, quantify the risk in such farming via sensitivity analyses on production costs, biological yield, and farm gate prices, and allow comparison of integrated farming economics with monoculture farms. The model will be an adaptation and extension of models previously developed for shellfish aquaculture operations, including those for blue mussels and scallops (Kite-Powell *et al.* 2003; Kite-Powell 2011; see attached CV), and for sugar kelp farming (Kite-Powell 2016). It will be implemented as a spreadsheet for easy dissemination and use by a range of interested parties as a business-planning tool.

II.3   Relevance to NOAA Sea Grant Aquaculture Research Program objective:

This project will develop novel, affordable and practical methods to integrate mussel and kelp farming. The work falls well within Sea Grant's "Sustainable Fisheries" priority area. Of the four topical priority areas listed in the RFP, we will directly address 2b - "Research that supports the increase in production of new and emerging species of aquaculture interest (e.g. algae, bivalves)". The newly integrated culture methods proposed here will help propel economic growth planned by GreenWave and other aquaculture producers in Southern New England and LIS within 1 to 2 years of project completion.

III. PROJECT OUTCOME LOGIC MODEL

Outcome Summary: This research will advance marine aquaculture in the short-term by developing a working group of experts and stakeholders, engineering, testing, and simulation tools, all directed at integrating mussel culture with kelp culture. We expect this work will assist regulatory authorities in crafting regulations that are responsive to the needs of protected species and marine farmers while enabling the sustainable growth of shellfish and seaweed aquaculture. We expect that at least ten new or existing sub-tidal and offshore leases covering over 200 acres will modify their practices or adopt measures we develop within two years of the projects conclusion.

Inputs ➡	**Outputs** ➡		**Outcomes – Impact**		
	Activities	**Participation**	**Short Term**	**Medium Term**	**Long Term**
What we invest: Time and effort of: - 6 researchers - 3 industry collaborators - - 2 Sea Grant extension prof. Results of our prior and concurrent research Knowledge of participants, collaborators, workgroup Networks of industry and experts nationally and internationally	**What we do:** Develop and test new two-crop longline systems Develop and assess management Methods Evaluate different mussel density Develop and test array Evaluate yield and quality of Crops Develop economic model of co-culture versus Mono-culture	**Who we reach:** Shellfish growers Protected species biologist Regulatory Agencies State and Federal Resource Managers Buyers and processors of sustainable seafood Scientists in comparable fields in the region	**What the short term results are:** Industry and scientific engagement on aquaculture diversification Production and markets Engineering and management solutions that make a farm more productive and profitable (and reduce risk to protected species)	**What the medium term results are:** Growers and regulators will adopt the project's engineering and manage-ment solutions	**That the ultimate results are:** Robust, diversified production of kelp and mussels Without interaction between protected species Shellfish & seaweed aquaculture sector expands Solutions are adaptable to confront similar problems in other regions

Assumptions

- We have effective experts and advisors who can collaborate on useful solutions
- Effective gear modifications and management practices can be used productively grow kelp and mussels on the same "headrope" structures.

External Factors

- Cost of modifying and managing gear and permitting become cost prohibitive
- Shellfish farmers become discouraged and stop pursuing farming offshore
- Regulators remain concerned and inflexible about the suitability of longlines and risks to protected species or interference with other stakeholders.

Extension Component Output Activities

- Organize a meeting of participants, experts and stakeholders at Northeast Aquaculture Conference and Expo in January 2017 to review research plans, solicit input, and build an informal project working group (WG).
- Create a project page on the WHOI website for all activities and outputs and results, and as a conduit for coordination among PIs, participants and WG.
- Communicate through in-person contacts, list serves (eg. ECSGA, State Aquaculture Associations), and email lists.
- Present results through meetings: ex. NACE, Natl. Shellfish Assoc., WAS
- Project ending workshop/webinars
- Produce article(s) for association and industry magazine (eg: National Shellfish Association, Journal of WAS etc.)
- Peer-reviewed articles

Evaluation - How will you measure and report your outcomes?

We will evaluate the various advances of our research and extension portions in a variety of ways, and through several metrics. For example, during the research portion, we will measure the following:

- The level of engagement by industry and topic experts on longline and array modifications, effectiveness and risks.
- The effect of our innovative gear modifications on productivity and practical use within the mussel and kelp aquaculture industry.
- The efficacy of our outreach efforts based on the scale of audience (web page hits, number and type of attendees at workshops) and whether or not our gear innovations become adopted by industry and endorsed by regulatory agencies.

IV Milestone Chart:

Task	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
Install dual-purpose longline								
Dual-use management								
Density evaluation								
Kelp catenary array								
Yield and quality evaluation								
Develop Economic model								

V Outreach and Education Plan:

We will utilize the full range of outreach opportunities available in Southern New England with extension agents (see letters of collaboration and support, respectively from Diane Murphy, Cape Cod Cooperative Extension/Woods Hole Sea Grant, and Tessa Getchis, Connecticut Sea Grant) helping us summarize our results in ways to best reach the public and policy-makers. Early in the project, we will expand our engagement with stakeholders in the region by hosting a workshop at the Northeast Aquaculture Conference and Expo in January 2017 (Providence, RI).

Through cooperation with shellfish growers, town, state and federal officials, and scientists, we will report our results on our Project Website and through meetings, reports, and extension bulletins. Besides an opportunity to describe our work, the workshops will provide a forum to help regulatory bodies (such as Massachusetts Division of Marine Fisheries) reach ocean farmers with seaweed culture regulations they are crafting. Brief tutorials will be offered for important planning tools such as Connecticut Sea Grant's marine spatial GIS software, and WHOI aquaculture business planning workbook (Kite-Powell 2011). Presentations will also address the importance of farm designs that are responsive to the needs of protected species while enabling the growth of shellfish aquaculture. These forums will discuss our new methods for sub-tidal and offshore aquaculture, and feature participation by our cooperating farmers.

Outcomes of this study will be incorporated into GreenWave's farmer manual, an open source resource that will be available publicly on GreenWave's website, and shared directly with all farmer apprentices that train with GreenWave. Findings will also be incorporated into bi-annual farmer training workshops, during which farmers, such as members of the Noank Aquaculture Cooperative, learn hands-on how to install the multispecies farming model, seed, maintain crops, harvest, and remove the system.

A concluding workshop will be conducted with the marine farming community and associated agencies on the topics described above at the Northeast Aquaculture Conference and Expo scheduled for winter 2018. We intend to work directly with at least 3 farmers on > 30 acres in the first year, with the possible addition of interested growers in future years. We expect that at least ten sub-tidal and offshore leases covering over 500 acres of operations will modify their practices or adopt measures we develop within two years of the project's conclusion.

V Coordination with other program elements:

This project complements PI Lindell's currently funded Saltonstall-Kennedy (S-K) project NA14NMF4270035, "Developing Whale and Turtle-Friendly Sub-tidal Aquaculture Gear" and another one funded by the National By-catch Reduction Engineering Program (BREP). The S-K project, due to end summer 2017, has demonstrated advancements in anchoring technology for offshore aquaculture, and the utility of modifying or stiffening the vertical lines directly under buoys as a means of reducing risk to protected species.

This proposed project will follow a USDA-NIFA Funded project "Developing An Environmentally And Economically Sustainable Sugar Kelp Aquaculture Industry In Southern New England: From Seed To Market lead by co-PI Yarish and co-PI Lindell to make advances in the development of commercial seaweed nurseries and in the post-harvest processing of sugar kelp. Lindell is a co-PI on the project which is due to conclude August 2016.

This project also complements and will be coordinated with co-PI Goudey's recently approved NOAA SBIR project "Engineering Structures for Offshore Macroalgae Farming" that will identify and prove the feasibility of innovative, commercial-scale systems and methods for the cultivation of macroalgae on the high seas. Part of that project will generate drag data on cultured kelp, essential to the engineering of reliable systems for kelp culture.

The Massachusetts Division of Marine Fisheries (MA DMF) has allowed seaweed farming for the past 5 years only on the basis of scientific research, and only on existing shellfish leases. Currently there is no legal basis for issuing commercial seaweed farming leases other than in tandem with shellfish leases in MA. Authorities at DMF are supportive of our proposed initiative, and are eager to use this project and workshop opportunities as a means to communicate with stakeholders about the development of new regulations for kelp and seaweed culture that are under development and due to be released in 2017.

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